Possibility of complete polarizational phase conjugation via Stimulated Brillouin Scattering

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Abstract

Backward Stimulated Brillouin Scattering (SBS) is considered theoretically in the presence of birefringent inclusions that rapidly randomize polarization of propagating light. Local scalar hypersound mirrors do not conjugate polarization by themselves. However, completely conjugating specklon $\mathbf{E}_S(\mathbf{R}) = c\exp(gz/2)\mathbf{E}^*_{PUMP}(\mathbf{R})$ has better spatial overlapping with the pump profile in the presence of such inclusions. Therefore this specklon has twice larger gain g in comparison with all other non-conjugate scattered waves. Such gain discrimination should yield complete polarizational phase conjugation via backward SBS and thus should allow for double-pass compensation of birefringence-induced distortions introduced by laser elements.

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Spatial phase self-conjugation via backward Stimulated Brillouin Scattering (SBS) demonstrated by V. V. Ragulsky at al. in 1972, [1], is still one of the best and most reliable tools to produce high-fidelity time-reversed replicas of the incident laser pulses. One of the most important applications of phase conjugate waves is the double-pass compensation of the distortions introduced into laser beams by their propagation through amplifying elements of lasers. This compensation was suggested and demonstrated by O. Yu. Nosach et al., also in 1972, [2], and has been reproduced and used may times since, see e.g. publications [3, 4] and multiple reviews and books on phase conjugation, [5-10].

With all the advantages of the backward SBS for phase self-conjugation, it has one rather considerable drawback. Namely, SBS is realized via reflection of light by local "multilayer mirrors" formed by the compressions and rarefactions that propagate in the medium with the speed of hypersound. Those mirrors are implemented as scalar perturbations of dielectric susceptibility, and hence they handle polarization of reflected light as if they were usual mirrors. It means that the polarization vector of the locally reflected light tends to reproduce that vector of incident light without complex conjugation. Meanwhile, it is the completely conjugate reflected vector field, $\mathbf{E}_S(\mathbf{R}) = c\mathbf{E}^*_{PUMP}(\mathbf{R})$, that allows for the compensation of polarization inhomogeneities introduced into the beam by laser elements. The necessity to overcome inhomogeneous birefringence is especially acute for quasi-CW lasers with high pulse repetition rate, due to high thermal stresses induced in solid state laser elements.

Several schemes of complete polarizational phase conjugation has been discussed and realized up to now. Some of them deal with the properly arranged Four-Wave Mixing processes, see details in e.g., [7]. Stimulated Rayleigh Wing Scattering was suggested [11] and demonstrated experimentally [12] to be a process with natural phase conjugation of polarization. Phase conjugation via backward SBS in a scalar medium works well for the linearly polarized radiation, $\mathbf{E}_{PUMP}(\mathbf{R}) = \mathbf{e_P}E_{PUMP}(\mathbf{R})$, where $\mathbf{e_P} = \mathbf{e_P}^*$, $|\mathbf{e_P}| = 1$. In that case simple scalar conjugation is realized, $\mathbf{E}_S(\mathbf{R}) = \mathbf{e_P}E^*_{PUMP}(\mathbf{R})$, and it actually becomes polarizational conjugation as well, [13]. In this connection a scheme was suggested and realized, [14], to transform the beam with transversely inhomogeneous polarization into a linearly polarized beam with a larger (at least twice)

product of solid angle divergence times area. Splitting original beams into two linearly polarized components, rotating the polarization of one of them by 90°, and then combining them into common volume may accomplish that. It is the fundamental theorem of Geometric Optics and Classical Mechanics – the preservation of brightness, of phase space, of Lagrange-Helmholtz invariant – that prohibits such a combination without increase of the beam's area, or of the solid angle, or of both.

Still, such a solution presents its own technical inconvenience. Therefore there is still a great need in the direct method of complete polarizational phase conjugation via backward SBS. The present letter describes a possible scheme to do that.

Consider a standard isotropic SBS-active medium with a small volume fraction occupied by transparent birefringent inclusions, which rapidly randomize polarization of propagating light without much increase of the beam's angular divergence. Possible implementations of such inclusions will be discussed at the end of the letter. The incident "pump wave" that we want to conjugate may be partially polarized, completely depolarized or completely polarized. An important assumption is that this "pump" is generated by transmission of a single coherent beam through an aberrator or through a laser rod. Therefore we assume that this pump constitutes a definite spatial distribution of complex field vector, $\mathbf{E}_{\mathrm{PUMP}}(\mathbf{R})\cdot f(t)$, where $f(t)$ may or may not be monochromatic exponential $\exp(-i\omega t)$.

Parabolic wave equations for the undepleted pump wave $\mathbf{E}_{\mathrm{PUMP}}(\mathbf{R}) = \mathbf{P}(x,y,z)\exp(-ik_{\mathrm{P}}z)$ propagating in ($-z$)-direction, and for the signal wave $\mathbf{E}_{\mathrm{S}}(\mathbf{R}) = \mathbf{S}(x,y,z)\exp(+ik_{\mathrm{S}}z)$ propagating in (+z)-direction and subject to SBS-amplification, are

$$\frac{\partial P_j}{\partial z} + \frac{i}{2k}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)P_j(x,y,z) - i\beta_{jm}(x,y,z)P_m = 0 \qquad (1)$$

$$\frac{\partial S_j}{\partial z} - \frac{i}{2k}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)S_j(x,y,z) + i\beta_{jm}(x,y,z)S_m = (G/2)(\mathbf{P}^*\cdot\mathbf{S})P_j \qquad (2)$$

Tensor $\beta_{jm}(\mathbf{R})$ has dimensions of inverse meters; it describes random birefringent inclusions. Right Hand Side (RHS) of the Eq. (2) describes the recording of local scalar hypersound grating ($\mathbf{P}^*\cdot\mathbf{S}$) and its read-out by the pump wave $\mathbf{P}$. Intensity gain

coefficient g (1/meters) of SBS process for a linearly polarized pump, e.g. $\mathbf{P} = (\mathbf{x}\hat{})P$, is equal to $g = G|P|^2$. If $|P|^2$ is measured in Watt/m^2, then the SBS constant G has dimensions (m/Watt). Derivation of Eqs. (1, 2), except for birefringence terms, may be found in any book on phase conjugation. We assume that propagation of light in the presence of birefringent inclusions randomizes polarization at a short distance: short in comparison with the length of SBS gain $L_g = 1/g \approx 1/(G\mathbf{P}\cdot\mathbf{P^*})$ at the current intensity $\mathbf{P}\cdot\mathbf{P^*}$ of the pump.

Following the "ideology of specklon", see [7, 10], one should consider two radically different types of solutions of Eq. (2) for the signal **S**. One type describes the waves, which are spatially uncorrelated with the pump. Their propagation may be considered via substitution of the right-hand-side of Eq. (2) with its statistical average. Randomizing action of birefringent inclusions results in the following form of the correlation matrix for the pump,

$$\langle P_k P_m{}^* \rangle = 0.5\langle \mathbf{P}\cdot\mathbf{P^*} \rangle\, \delta_{km} \,,$$

in most of the interaction volume. Here δ_{km} is the 2-dimensional Kronecker symbol. Averaging of the RHS in Eq. (2) yields gain coefficient

$$g(\text{uncorrelated}) = (1/2)G\langle \mathbf{P}\cdot\mathbf{P^*} \rangle, \tag{3}$$

i.e. half of the value for linearly polarized pump with the same averaged intensity $\langle \mathbf{P}\cdot\mathbf{P^*} \rangle$. This result is in full agreement with the gain for uncorrelated waves by the totally depolarized pump in a usual isotropic SBS-active medium, i.e. without β-inclusions, see [13] or Section 5.4.1 in [7].

Solutions of other type to be considered are those with the signal, which is correlated with the components $P_x{}^*(\mathbf{R})$, $P_y{}^*(\mathbf{R})$ of the conjugate pump field. It is here that the <u>radical difference</u> appears between our medium with depolarizing inclusions and SBS in a simple isotropic medium. Namely, randomizing $\beta_{jm}(\mathbf{R})$-inclusions couple the polarizational components of correlated specklon in all the interaction volume. Therefore <u>the only correlated specklon</u> that satisfies Eq. (2) with β-terms, but without RHS, is $\mathbf{S}(\mathbf{R}) = c\mathbf{P^*}(\mathbf{R})$. Such signal wave realizes the <u>complete polarizational phase conjugation</u> of the incident pump wave.

Calculation of the gain coefficient g for this specklon, $\mathbf{S}(\mathbf{R}) = \exp(gz/2)\mathbf{s}(\mathbf{R})$, follows the standard specklon procedure, [7, 10]. One has to project RHS of Eq. (2) to the normalized profile of specklon, $\mathbf{s}(\mathbf{R}) = \mathbf{P}^*(\mathbf{R})/\{\langle \mathbf{P}\cdot\mathbf{P}^*\rangle\}^{1/2}$ and then to average over the ensemble of the depolarized speckle-field $\mathbf{P}^*(\mathbf{R})$. Gaussian statistics allows one to write:

$$\langle P_i P_k P_m^* P_n^*\rangle = \langle P_i P_k\rangle\langle P_m^* P_n^*\rangle + \langle P_i P_m^*\rangle\langle P_k P_n^*\rangle + \langle P_i P_n^*\rangle\langle P_k P_m^*\rangle =$$

$$= (1/4)\,\langle \mathbf{P}\cdot\mathbf{P}^*\rangle^2(\delta_{im}\,\delta_{kn} + \delta_{in}\,\delta_{km}). \qquad (4)$$

Here we used the relationship $\langle P_i P_k\rangle = \langle P_m^* P_n^*\rangle = 0$. One then gets the gain for the completely conjugating specklon:

$$g(\text{specklon}) = (1/2)G\langle \mathbf{P}\cdot\mathbf{P}^*\rangle, \qquad (5)$$

i.e. twice larger than the gain for the uncorrelated components from Eq. (3). This factor 2 is the same, as the discrimination factor in favor of conjugate specklon in the case of a linearly polarized pump. Therefore one should expect the same favorable condition for the raise of this complete polarizational phase conjugate specklon from seeding input.

There is a price one should pay for these remarkable properties. First, depolarized pump yields both values of gain, uncorrelated and specklon's, both proportionally smaller than those for a linearly polarized pump of the same average power density $\langle \mathbf{P}\cdot\mathbf{P}^*\rangle$. Second, depolarizing inclusions may (and may not) introduce extra contamination and additional centers of optical heating and breakdown, which are especially troublesome for the lasers with high repetition rate and average power.

As for the ways to introduce depolarizing inclusions, one may consider putting pieces of birefringent material (crystals, glasses, polymers, gels, etc.) into SBS-active liquid. An important requirement is that those pieces introduce transversely inhomogeneous birefringence. Inhomogeneous stress regions in solid SBS-media are also a possibility. We hypothesize also that depolarization of light due to propagation in a circular waveguide (solid or filled with a liquid) may serve the purpose described above.

To conclude, the method of complete polarizational phase conjugation in the backward Stimulated Brillouin Scattering is suggested. One should embed transversely inhomogeneous birefringent inclusions into the usual isotropic SBS medium all over the length of the pump-signal interaction, with the goal to couple polarization components and thus to positively select the completely conjugating signal wave.

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Possibility of complete polarizational phase conjugation

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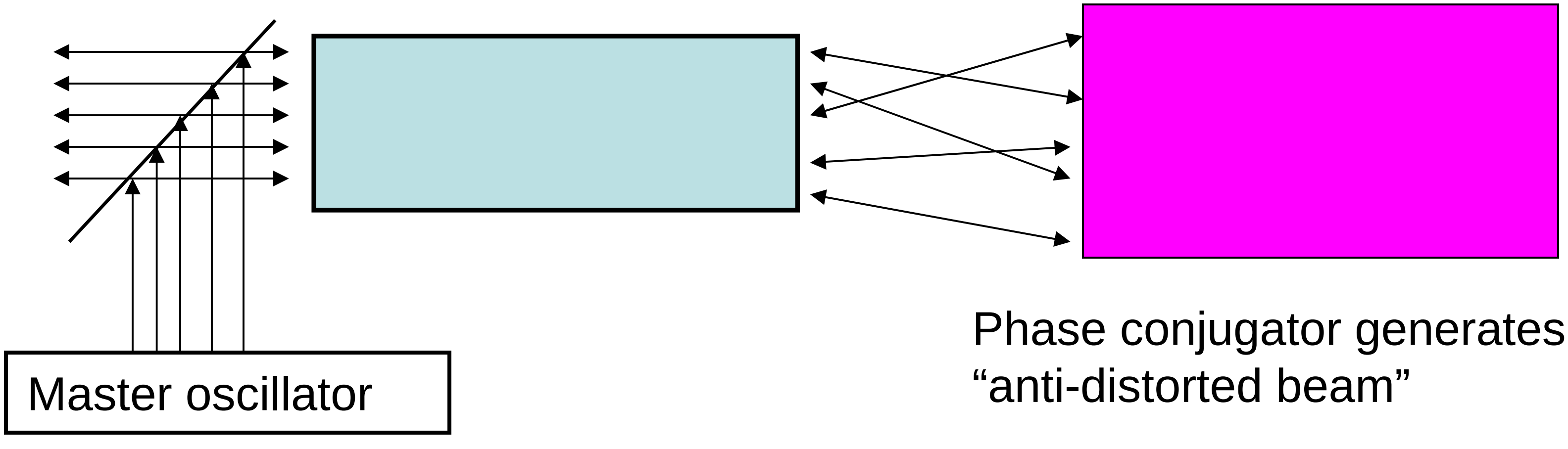
Overview of the talk

1. Phase conjugation as a tool for beam correction.
2. Polarization properties of Backward SBS (Stimulated Brillouin Scattering).
3. Basic equations in paraxial steady-state approximation
4. Speckle-modes in the presence of depolarizing elements
5. Gain coefficient for completely conjugate specklon
6. Conclusion

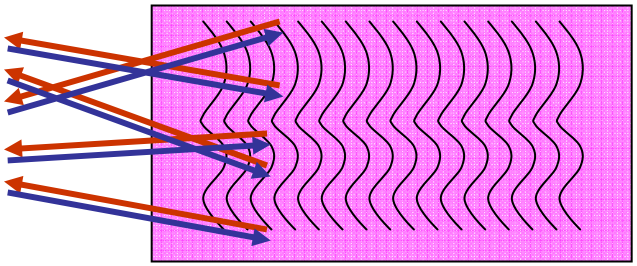
Phase conjugation as a tool for improvement of laser beam divergence

Laser amplifier with inevitable phase inhomogeneities



Phase conjugator generates "anti-distorted beam"

Polarizaton properties of B-SBS:
Backward Stimulated Brilloiun Scattering

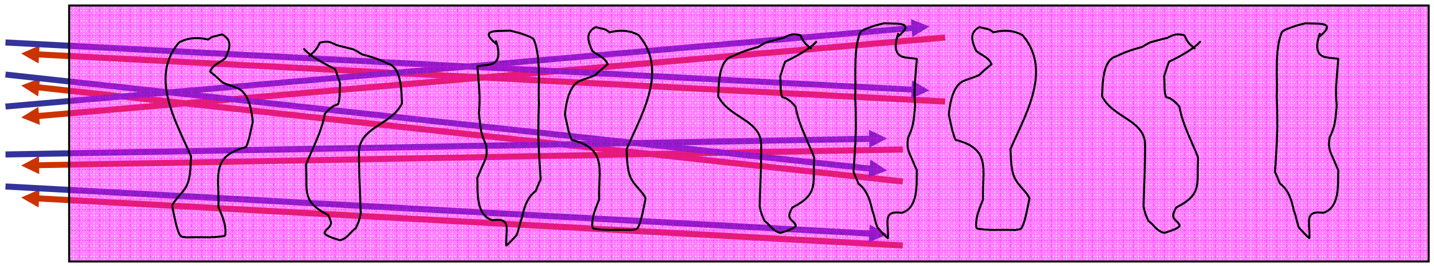


Reflection from volume grating of hyper-sound wave is similar to reflection from a mirror:

it preserves polarization vector, instead of time-reversing (conjugating) it !

Suggested in this work:

<u>To introduce multiple depolarizers on the path of the beams</u>



System of basic equations in steady-state paraxial approximation

$$\frac{\partial P_j}{\partial z}+\frac{i}{2k}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)P_j(x,y,z)-i\beta_{jm}(x,y,z)P_m=0 \qquad (1)$$

$$\frac{\partial S_j}{\partial z}-\frac{i}{2k}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)S_j(x,y,z)+i\beta_{jm}(x,y,z)S_m=(G/2)(\mathbf{P}^{*}\cdot\mathbf{S})P_j \qquad (2)$$

Here **P** is pump (incident) field,

S is scattered field

(the one we want to be conjugate of the pump),

β_{jm} are random depolarizing inclusions.

Scattered wave modes un-correlated with the depolarized pump

$$\mathbf{S}_{\text{uncorr}}(x, y, z) \propto \exp\left[G\left\langle \mathbf{P} \cdot \mathbf{P}^* \right\rangle z / 4\right]$$

Here $G \cdot P_x \cdot P_x{}^*$ is intensity gain coefficient (1/m)

for plane wave of linearly polarized pump **P**.

Scattered wave modes which are completely conjugate of the depolarized pump

$$\mathbf{S}_{\mathrm{conj}}(x,y,z) \propto \mathbf{P}(x,y,z)\exp\left[G\left\langle \mathbf{P}\cdot\mathbf{P}^{*}\right\rangle z/2\right]$$

We see that the gain of conjugate mode is twice that of the un-correlated modes

Drawbacks of this method of complete polarizational phase conjugation

We must pay the price for the use of depolarizers. Gain values, both for the conjugate signal and for un-correlated modes, are proportionally diminished by factor 2.

Nevertheless, the discrimination factor,

$g(\text{conjugate}) / g(\text{un-correlated}) = 2$,

is good, just like in a standard B-SBS conjugation.

Conclusion

1. Modification of the B-SBS phase conjugation scheme is suggested.
2. This scheme promises to deliver complete polarizational phase conjugation.
3. Possible implementation of depolarizing elements: propagation in a circular light-guide.
4. Future work: to model propagation numerically, to try in laboratory experiment.